The Astrophysical Journal, 521:839–843, 1999 August 20


# ON PHOTOSPHERIC FLUORESCENCE AND THE NATURE OF THE 17.62 Å FEATURE IN SOLAR X-RAY SPECTRA

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*Received 1999 January 26; accepted 1999 March 30*

## ABSTRACT

The identification of the emission-line feature at 17.62 Å in solar X-ray spectra is reexamined. Using a Monte Carlo technique, we compute a realistic theoretical upper limit to the observed Fe L$\alpha$ photospheric fluorescent line strength caused by irradiation from an overlying corona. These calculations demonstrate that the photospheric Fe L$\alpha$ characteristic line is much too weak to account for the observed 17.62 Å line flux. Instead, we identify this line with the configuration interaction $2s^2 2p^4 3p$ $^2P_{3/2}$–$2s2p^6$ $^2S_{1/2}$ transition in Fe XVIII seen in Electron Beam Ion Trap spectra and predicted in earlier theoretical work on the Fe XVIII X-ray spectrum. This line should be easily resolved and detected in stellar coronae by the spectrographs on the upcoming *Chandra X-ray Observatory* and *X-ray Multi-mirror Mission.*

*Subject headings:* atomic processes — line: formation — line: identification — Sun: corona — Sun: X-rays, gamma rays

## 1. INTRODUCTION

The soft X-ray (longward of 1 Å) solar spectrum is dominated by lines arising in high-charge states of Fe in addition to line complexes due to He-like and H-like ions of Fe and abundant lighter elements. These lines are formed at temperatures ranging from about $10^6$ to several $10^7$ K. Over the last 30 years or so, X-ray spectroscopy of the solar corona performed using different satellite and rocket-borne instruments, coupled with progress in identifying the different transitions responsible for the observed features, has provided valuable diagnostics of the state of both flaring and quiescent coronal plasma.

One particular feature near 17.6 Å observed in X-ray spectra obtained by several different instruments has proved difficult to interpret. It was first identified as the photospheric Fe L$\alpha$ characteristic line, arising from inner-shell ionization by coronal X-rays (McKenzie et al. 1980; Phillips et al. 1982). However, this has subsequently been questioned on the grounds that the observed line is both stronger than expected and that its observed wavelength and width do not quite correspond to that of Fe L$\alpha$ (McKenzie & Landecker 1982; Acton et al. 1985). Two other candidate identifications have been advanced: a second order Fe XXIII line at 8.815 Å (Fawcett et al. 1987) and an Fe XVIII line predicted in a theoretical investigation of the Fe XVIII spectrum (Cornille et al. 1992).

While photospheric fluorescent lines have been only of passing interest in the solar spectrum, they could be of profound importance in the study of coronae on stars other than the Sun. Photospheric fluorescent lines are produced when X-ray photons from the hot ($T \gtrsim 10^6$ K) overlying corona ionize neutral, or near-neutral, atoms or ions by removing an inner-shell electron. The resulting excited states of these atoms can decay by radiative transition, producing the "characteristic" X-ray lines. As pointed out by Bai (1979) in the case of the solar Fe K$\alpha$ lines, for a given coronal X-ray spectrum the observed fluorescent line flux depends on the photospheric element abundances, the height of the emitting source, and the angle between the emitting source and the observer. If either the emitting geometry or the photospheric abundances are known, the fluorescent lines can provide information on the other of these parameters. In the case of stellar coronae, which cannot yet be spatially resolved, fluorescent lines can then provide unique insights into the spatial geometry of the emitting regions.

The 17.62 Å feature should be well resolved and detected by the spectrometers on the *Chandra X-ray Observatory* (*CXO*) and the *X-ray Multimirror Mission* (*XMM*). The approaching launches of these instruments (*CXO* in 1999; *XMM* in 2000), together with the potential diagnostic value of the Fe L$\alpha$ line for stellar coronae, motivates us to reexamine the nature of the 17.62 Å feature and determine whether or not it could indeed be due to photospheric fluorescence.

In this paper, we describe Monte Carlo calculations of the photospheric emission caused by irradiation by an overlying coronal X-ray spectrum. These calculations were performed in order to provide a realistic estimate of the expected emergent Fe L$\alpha$ line strength. We demonstrate that the photospheric Fe L$\alpha$ line is very weak and can only account for a very small fraction of the observed 17.62 Å feature. Instead, we argue that a feature observed in Electron Beam Ion Trap (EBIT) Fe XVIII spectra at 17.62 Å as part of ongoing laboratory astrophysics measurements cataloging the L-shell iron emission (Brown et al. 1998, 1999) and predicted by theory (Cornille et al. 1992; D. Liedahl 1998, private communication) is instead the same feature observed in solar X-ray spectra.

We discuss earlier work concerning the 17.62 Å feature in § 2; in § 3 we present Monte Carlo calculations of the expected fluorescent Fe L$\alpha$ flux; we describe EBIT observations of the Fe XVIII X-ray spectrum in § 4; and we draw conclusions in § 5.

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## 2. THE 17.62 Å FEATURE IN SOLAR X-RAY SPECTRA

The spectral feature near 17.62 Å is visible in the *Orbiting Solar Observatory* (*OSO*) *III* flare spectrum of Neupert et al. (1967), as well as in spectra obtained by the *OV1-10* satellite presented by Rugge & Walker (1968) and Walker & Rugge (1969), but it was not identified in these papers. Later spectra obtained by SOLEX (McKenzie et al. 1980), the *Solar Maximum Mission* (*SMM*) (Phillips et al. 1982), and a rocket-borne spectrometer (Acton et al. 1985) also detected this feature. McKenzie et al. (1980) tentatively identified it with the inner-shell $n = 3$–2 (M4,5–L3) transition in neutral, or once-ionized, Fe. This line would then be the result of fluorescence of the "cold" photosphere by coronal X-ray photons. The same identification was adopted by Phillips et al. (1982). McKenzie & Landecker (1982) subsequently questioned the identification on wavelength and intensity grounds. From SOLEX B spectra they determined a wavelength of 17.626 Å, which is somewhat longward of the laboratory wavelength of $17.59 \pm 0.02$ Å (Bearden 1967). They also suggested the observed feature appeared stronger than one might expect from fluorescence. Based on a solar flare spectrum in the 10–100 Å range obtained from a rocket flight, Acton et al. (1985) later rejected the Fe L$\alpha$ identification on both wavelength and line-width grounds. Their observed wavelengths for the feature were 17.618 Å in first order and 17.621 Å in second order, both of these being discrepant with respect to the laboratory value. Moreover, they noted that the laboratory line is broader than the feature in their spectra (however, we note parenthetically that the widths of laboratory lines formed by electron impact on targets in solid state are likely to be broader than their gas-phase counterparts).

The identification problem was suggested as being solved by Fawcett et al. (1987), who noted that the Fe XXIII $2s2p\ ^1D$–$2s4d\ ^1D$ transition they identified in *SMM* spectra at 8.815 Å would appear in second order at 17.63 Å. However, it is not obvious to us that this could provide a significant contribution, because other nearby strong lines in the same spectra, such as Fe XXIII 8.906 Å and Fe XXII 8.976 Å, are not apparent in second order in other solar spectra that clearly show the 17.63 Å line.

A theoretical investigation of the Fe XVIII X-ray spectrum by Cornille et al. (1992) provides a further possible candidate for the observed feature. These calculations predict an unexpected line at 17.61 Å corresponding to the transition energy between the levels $2s^22p^43p\ ^2P_{3/2}$ and $2s2p^6\ ^2S_{1/2}$. This transition does not exist in calculations where configuration mixing is not taken into account and, therefore, is missing from older predictions and line lists. The lower level is comprised of a mixture of the even parity configurations $2s2p^6$, $2s2p^53p$, $2s^22p^43s$, and $2s^22p^43d$. The $2s^22p^43p\ ^2P_{3/2} \rightarrow 2s2p^6\ ^1S_{1/2}$ transition is, therefore, enabled by the (small) admixture of the $2s^22p^43s\ ^2S_{1/2}$ level to the lower level. HULLAC calculations, which are designed to include configuration mixing, also predict this transition. The wavelength calculated by HULLAC is 17.66 Å (D. A. Liedahl 1998, private communication). Cornille et al. (1992) noted that the predicted transition probability was quite large and proposed the Fe XVIII line as a possible identification of the solar feature.

Laboratory X-ray astrophysics measurements at the Livermore Electron Beam Ion Trap facility have cataloged the L-shell transitions of Fe XVII through Fe XXIV (Brown et al. 1998, 1999). These measurements, described in § 4, have clearly identified a line at 17.62 Å from Fe XVIII and provide the most unambiguous evidence of the identity of the 17.62 Å feature.

## 3. CALCULATING THE Fe L$\alpha$ FLUORESCENT LINE FLUX

Since we are interested in determining the reality or otherwise of significant emergent Fe L$\alpha$ flux, we have adopted a thin shell spherical geometry rather than more realistic but more complicated extended geometries. The corona is then assumed to be an infinitely thin emitting layer lying close to a cold, semi-infinite photospheric slab. In these calculations, we assumed the height of the corona above the solar surface to be 0.01 $R_\odot$. This is smaller than the typical observed coronal scale height in soft X-rays. However, this geometry should yield close to the highest possible emergent fluorescent line flux from a given ionizing coronal spectrum, because there is essentially no dilution of the source flux as a result of sphericity or height of the source above the photosphere.

Calculations were performed for two different incident coronal spectra. Both were isothermal model spectra calculated using an updated version of the optically thin plasma model of Mewe, Gronenschild, & van den Oord (1985). We adopted temperatures of 0.34 and 1.0 keV. The hotter temperature is typical of solar flares, as well as the coronae of active stars, flare stars, and RS CVn systems during quiescence. The cooler temperature corresponds to the rough temperature where the quiescent solar emission measure distribution peaks. The coronal spectral models do not include the 17.62 Å Fe XVIII line described in § 4.

We have adopted a Monte Carlo approach that samples a coronal spectrum and follows photons through the photospheric layer as they undergo, probabilistically, interactions with the photospheric gas. These interactions are Compton scattering and photoabsorption by inner-shell electrons. In the case of photoabsorption, there is a finite probability, given by the appropriate fluorescence yield, of producing a characteristic photon from the decay of the excited ionized state. In this case, photons are emitted isotropically and are again followed through the photospheric slab. A more detailed description of these methods will be given in a later paper.

For our calculations we have adopted photospheric abundances of Anders & Grevesse (1989), except for Fe, for which we adopt the value Fe/H = 7.50 (on the usual spectroscopic logarithmic scale where H/H = 12.0) based on Holweger, Heise, & Kock (1990) and Biémont et al. (1991). Photoionization cross sections are from the Hartree-Dirac-Slater calculations of Verner et al. (1993) and Verner & Yakovlev (1995). The fluorescent yields for Fe L were taken from Browne & Firestone (1986). The Fe L$\alpha$ wavelength of 17.59 Å is from Bearden (1967); we distinguish between Fe L photoionization from the L1 and from the combined L2 and L3 levels, producing either a 15.65 Å fluorescent line (L$\beta_3$ and L$\beta_4$) following ionization from L1, or 17.59 Å (corresponding to L$\alpha_1$ and L$\alpha_2$) following ionization from L2 or L3, with a fluorescent yield weighted by the relative subshell occupancy of L3, $Y = (4/6)0.566$. The L$\beta_1$ (M4–L2) line at 17.27 Å is not distinguished separately.

One might question the assumption of a cold slab to approximate the fluoresced solar atmosphere. The dominant source of Fe L photoionization events is from incident photons immediately shortward of the photoionization edges near 17.5 Å. At this wavelength the total photoabsorption cross section of a neutral or once-ionized plasma, such as that characterizing solar chromospheric and photospheric material, is insensitive to the exact ionization stages of the constituent species. However, the exact wavelength of an emitted Fe L$\alpha$ photon is dependent on the ionization stage of the parent Fe ion. In this regard the extent of ionization of Fe at the height in the atmosphere where the material is becoming optically thick to the relevant ionizing photons could be important: if the plasma at the characteristic height for absorption is no longer nearly neutral, the fluoresced L$\alpha$ lines could be significantly shifted toward higher energies, depending on the degree of Fe ionization, and will not arise at all for ionization states above Fe IX.

To verify our assumptions, we have calculated the point in the solar atmosphere at which an optical depth of unity is reached in the vicinity of the Fe L photoionization edges. For this calculation we adopted the Vernazza, Avrett, & Loeser (1981) model C, which describes the solar atmospheric structure as a function of depth, and again used the photoionization cross sections of Verner et al. (1993) and Verner & Yakovlev (1995). Optical depth of unity near 17.5 Å occurs at about the temperature minimum in the solar atmosphere, placing the characteristic height for the generation of Fe L$\alpha$ photons at the top of the photosphere. At this point in the solar atmosphere, of order 75% of Fe is in the form of $Fe^+$. Multiconfiguration Dirac-Fock calculations of the Fe L$\alpha$ wavelength indicate a difference of only 0.004 Å between the lines due to neutral and once-ionized Fe (M. Chen 1999, private communication)—not noticeable at the resolution of existing spectra. Hence we conclude that approximating the solar atmosphere as a cold slab for our fluorescence calculations is valid.

The emergent fluorescent and Compton-reflected photospheric spectrum in the vicinity of Fe L$\alpha$ for the case of the 0.34 keV model is illustrated in Figure 1, together with the combined coronal and photospheric observed spectra. We draw attention to the photospheric spectrum in which some redistribution toward longer wavelengths of the incident spectral lines is apparent as a result of Compton scattering.

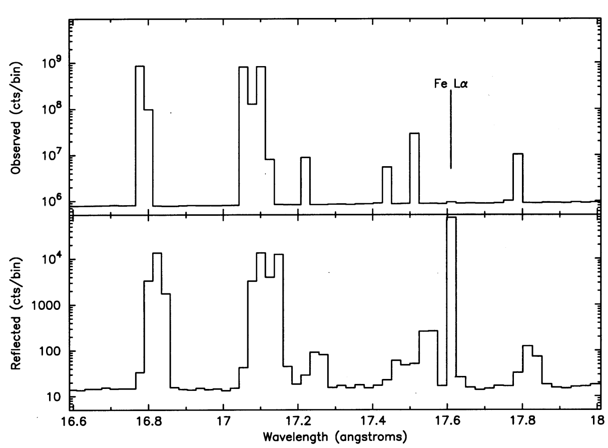


FIG. 1.—Monte Carlo simulation of observed (*top*) and reflected (*bottom*) spectra of a 0.34 keV isothermal coronal shell in the region of the Fe L$\alpha$ characteristic line. The coronal shell is located at height $h = 0.01R$ above a stellar surface of radius $R$. The observed spectrum includes both direct emission from the corona and emission reflected from the surface and emitted toward the observer. The fluorescent Fe L$\alpha$ line is very weak, amounting to only a few percent of the incident spectrum continuum level for the bin size shown (0.025 Å; 1 eV).

While a significant fluorescent line corresponding to the Fe L hole transitions is also readily apparent in the emergent spectrum, when this is compared to the combined spectrum it is clear that it amounts to only a small fraction of the incident coronal continuum level. In the case of the 1.0 keV model, the fluorescent line was even weaker. This is likely the result of there being more lines in the cooler model to provide flux to ionize the Fe L inner shells.

In contrast to Fe K fluorescence (e.g., Bai 1979), a weak Fe L feature results because of the combination of the lower fluorescence yield for Fe L and the lower probability of producing an Fe L hole due to the competing presence of low-$Z$ elements with substantial photoabsorption opacities.

Our sampling of the incident spectrum in the vicinity of 17.6 Å corresponds to a bin size of 0.025 Å (which places the Fe L$\alpha$ line slightly longward of 17.59 Å), or a resolving power of 350. This is similar to the expected performance of the *CXO* High Energy-Transmission Grating Spectrometer (HETGS) at this wavelength (the HETG resolving power is likely to be slightly higher). It is clear from Figure 1 that the Fe L$\alpha$ fluorescent feature is unlikely to be detected in such spectra, even in the absence of any coincident features in the incident spectrum. The detection or not of emission-line features against a continuum depends on the line-to-continuum contrast, which can be represented by the line *equivalent width*. Our predicted equivalent width for the Fe L$\alpha$ line appropriate to the 0.34 keV coronal incident spectrum is $\sim 2.5$ mÅ, which, for a resolving power of $\sim 500$ or so, requires for a detection at a significance level of $\gtrsim 3\ \sigma$ a signal-to-noise ratio of $\gtrsim 20$ in the continuum. Such a signal-to-noise ratio in the continuum cannot be obtained from stellar sources with near-future (*CXO* and *XMM*) X-ray spectrographs in feasible exposure times.

## 4. EBIT OBSERVATIONS

The Lawrence Livermore Electron Beam Ion Trap (EBIT) facility provides unique opportunities for performing X-ray spectroscopic measurements in a controlled, well-diagnosed environment, and has been exploited for this purpose in an ongoing, NASA-funded laboratory astrophysics effort for several years (Kahn et al. 1998; Beiersdorfer et al. 1998). One facet of the ongoing research is to establish a complete catalog of iron L-shell transitions in the 6–17 Å region in response to needs generated by the modeling of existing data from *ASCA* and future data from *CXO* and *XMM*. The EBIT device employs a monoenergetic electron beam that interacts with the iron ions in the trap to produce a collection of iron ions in a nearly pure charge state characteristic of the energy of the beam (Beiersdorfer et al. 1993). Different charge states are selected by setting the energy of the electron beam to the appropriate energies. The electron beam also excites the trapped ions, and the resulting line emission is recorded using specially developed X-ray spectrometers. Line identification is clearly facilitated by selecting the charge state of interest and thus knowing which charge states of iron are in the trap.

A spectrum of the iron L-shell line emission in the 16.6–18.0 Å region recorded by setting the beam energy to 1200 eV is shown in Figure 2*a*. At this beam energy no charge states higher than Fe XVII can be produced. Moreover, this energy is well above the energy (489 eV) to ionize Fe XVI, so that the trap contains Fe XVII ions almost exclusively. The lines seen in the spectrum in Figure 2*a* can therefore be

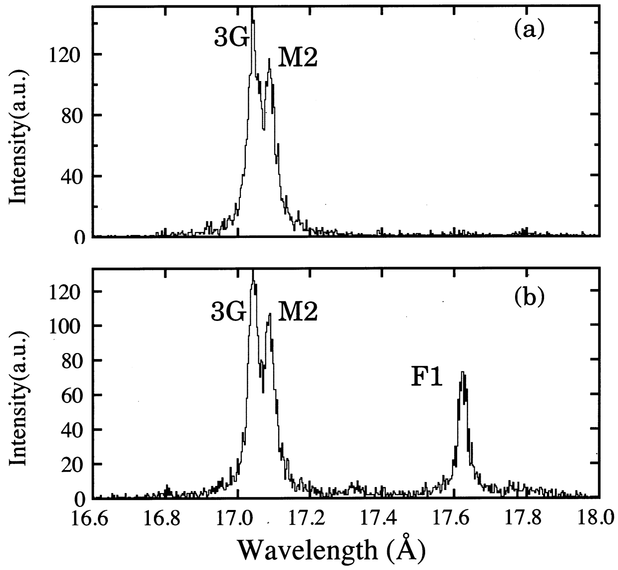


FIG. 2.— L-shell iron spectra in the 16.5–18 Å range observed at the Livermore EBIT facility: (*a*) electron energy set to 1200 eV, and only Fe XVII ions are produced; (*b*) electron energy set to 1300 eV, and both Fe XVII and Fe XVIII ions coexist in the source. The lines labeled $3G$ and $M2$ are transitions in iron Fe XVII and correspond to the transitions from upper levels $2p^5 3s\ ^1P_1$, $2p^5 3s\ ^3P_1$, and $2p^5 3s\ ^3P_2$, respectively, to the $2p^6\ S_0 1$ neonlike ground state. These lines are seen in both spectra. The prominent line near 17.6 Å, labeled F1, is only seen in (*b*) and corresponds to the transition $2s^2 2p^4 3p\ ^2P_{3/2}$–$2s2p^6\ ^2S_{1/2}$. We identify this line as being almost wholly responsible for the feature observed in solar X-ray spectra at 17.62 Å.

readily identified as two of the three strong $3s \rightarrow 2p$ transitions, $3G$ and $M2$ (also sometimes labeled $3H$; the third, $3F$, lies outside the region shown) in iron Fe XVII (Beiersdorfer & Wargelin 1994). Here we use standard notation referring to the transitions from upper levels $2p^5 3s\ ^3P_1$, and $2p^5 3s\ ^3P_2$, respectively, to the $2p^6\ ^1S_0$ Fe XVII ground state.

Figure 2*b* shows the iron L-shell line emission in the 16.6–18.0 Å region resulting from setting the beam energy to 1300 eV. This energy is above the ionization potential of Fe XVII at 1263 eV but below the 1356 eV ionization potential of Fe XVIII. At this energy a substantial fraction of Fe XVIII ions are produced resulting in strong Fe XVIII L-shell line emission from $3d \rightarrow 2p$ transitions situated at 14–16 Å (Brown et al. 1999). An Fe XVIII line, labeled $F1$, can also be seen in the spectrum in Figure 2*b* covering 16.6–18.0 Å. This line is situated on the long-wavelength side of the two visible $3s \rightarrow 2p$ Fe XVII transitions, matching the line predicted in the calculations by Cornille et al. (1992).

Like the wavelength of the Fe XVII lines in that wavelength region (Beiersdorfer & Wargelin 1994; Brown et al. 1998), the wavelength of the Fe XVIII line could be measured accurately by noting that its position falls among the well-known O VII K-shell transitions. In particular, the Fe XVIII line falls in between the $1s4p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ and $1s5p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ transitions (Beiersdorfer & Wargelin 1994) at 17.7673 and 17.3952 Å, respectively. Using the O VII lines as reference standards we determined the Fe XVIII wavelength to be $17.623 \pm 0.002$ Å.

The $17.623 \pm 0.002$ Å line $F1$ is the only Fe XVIII line in this wavelength region. Because the line originates from the upper level $2s^2 2p^4 3p\ ^2P_{3/2}$, which has odd parity, it cannot decay to the $2s^2 2p^5\ ^2P_{3/2}$ Fe XVIII ground level, which also has odd parity. Instead it decays to the $2s2p^6\ ^2S_{1/2}$ level, as noted in § 2, which has the required even parity. Since the level decays to a level with energy substantially above the Fe XVIII ground, the resulting line is well separated in wavelength from all other prominent Fe XVIII lines. As Cornille et al. (1992) have demonstrated, inclusion of this transition has a demonstrable impact on the theoretically derived strengths of other prominent lines of Fe XVIII. Conversely, its omission could lead to significant errors in theoretical computations of the Fe XVIII spectrum. We also note that this line feeds the upper level of the prominent 93 Å Fe XVIII line that plays an important diagnostics role in spectra observed with the *Extreme Ultraviolet Explorer* (e.g., Brown 1996; Dupree, Brickhouse, & Hanson 1996; Laming & Drake 1999). The 17.62 Å line should be easily resolved and detected in stellar coronae that have significant emitting plasma at temperatures where Fe XVIII ions are present ($\log T \sim 6.8$) by the spectrographs on the upcoming *CXO* and *XMM* missions. Combined with the 93 Å line, the 17.62 Å transition could be a useful diagnostic of cooler plasmas that are not in collisional equilibrium (e.g., a recombining plasma). In this case, collisional excitation of $n = 2$–3 transitions, including 17.62 Å, will be small or absent, but other Fe XVIII $n = 2$–3 transitions can still be produced from levels populated by electron capture, especially the $3s \rightarrow 2p^5\ ^2P_{3/2}$ transitions as well as others ending in the $2s^2\ 2p^5\ ^2P_{3/2}$ ground level.

## 5. CONCLUSIONS

We have shown by means of Monte Carlo calculations that the feature at 17.62 Å in solar X-ray spectra does not have any significant contribution from the Fe L$\alpha$ characteristic line resulting from fluorescence of photospheric layers by irradiation from an overlying X-ray emitting corona. The fluorescent line, while strong compared to the Compton reflected coronal incident spectrum, is very weak relative to the incident coronal X-ray continuum at $\sim$17.6 Å.

We identify the observed solar feature as being almost wholly due to the $2s^2 2p^4 3p\ ^2P_{3/2}$–$2s2p^6\ ^2S_{1/2}$ transition in Fe XVIII seen in Electron Beam Ion Trap spectra and predicted in earlier theoretical work on the Fe XVIII X-ray spectrum by Cornille et al. (1992) and by recent HULLAC computations (D. Liedahl 1998, private communication). The transition arises because of configurational mixing between the even parity configurations $2s2p^6$ and $2s^2 2p^4 3s$, and results from the electronic transition $3p \rightarrow 3s$ between $2s^2 2p^4 3p$ upper and $2s^2 2p^4 3s$ lower levels.

This transition is not included in existing commonly available X-ray spectral models that do not consider such configuration mixing. The line resulting from this transition should be easily resolved and detected in observations of stellar coronae using the spectrographs on the upcoming *CXO* and *XMM* missions.

We would like to thank Dimar Verner for making available his routine for calculating photoionization cross sections, Duane Liedahl for communicating to us results from HULLAC calculations for Fe XVIII, and Mau Chen for providing a multiconfiguration Dirac-Fock calculation of the energy difference between the L$\alpha$ transitions of neutral and once-ionized Fe. J. J. D was supported by the Chandra X-ray Center NASA contract NAS8-39073 during the course of this research. J. J. D would also like to extend warm thanks to Ken Phillips and Brad Wargelin for interesting and enlightening discussions, and to Verne Jacobs for information concerning theoretical and laboratory work on Fe inner-shell transitions. D. A. S. is supported in part by NASA/Marshall Space Flight Center under cooperative agreement NCC8-65, SUB96-077-030 from the University of Alabama in Huntsville. The work at Lawrence Livermore National Laboratory was performed under the auspices of the Department of Energy under contract W-7405-Eng-48 supported by a NASA High-Energy Astrophysics X-Ray Astronomy Research and Analysis grant NAG5-5123 to Columbia University and work order W-19127 to LLNL. Finally, we thank the anonymous referee for helpful corrections to our text.

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